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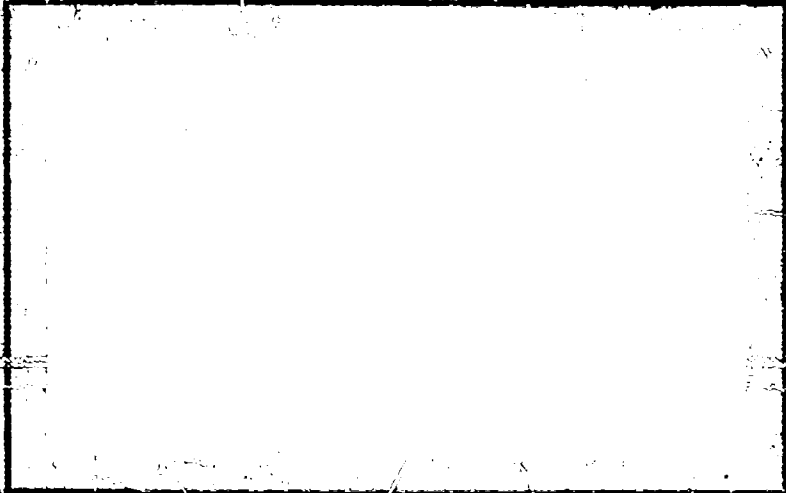
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Vapor Pressure of Sea Salt Solutions

by

C. F. Kientzler

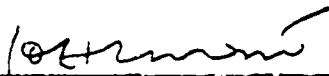
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ABSTRACT

A technique for the measurement of vapor pressure of sea salt solutions at relatively low temperatures (freezing to 30°C) is described, and vapor pressure measurements are reported. The previously reported results of Higashi (1931) at temperatures from 30°C to 175°C have been re-smoothed and tied in with the results of this investigation.

I. INTRODUCTION

Accurate information on the vapor pressure of sea salt solutions ranging in concentrations from dilute sea water to saturated solutions is of primary importance to meteorologists and oceanographers. This information is necessary in the determination of atmospheric sea salt nuclei by "isopiestic" method (Woodcock and Gifford, 1949). It is also useful in the study of the sea salt nuclei that may act as condensation nuclei in the formation of sea fogs and clouds as well as of nuclei at cloud bases that may account for production of rain from small clouds at temperatures above 0°C.

Information regarding the vapor pressure of sea water has been published by Higashi, et al, 1931, for a temperature range of 25°C to 175°C and for concentrations up to saturation. A table of vapor pressure of sea water of salinity 35 ‰ for temperatures from freezing to 32°C is given in Sverdrup, et al, 1942. Higashi's data were obtained by direct experimental measurement while Sverdrup's are inferred from measurements of other parameters. However, no information based on direct experimental results from freezing point to 25°C has been reported. The primary purpose of this paper is to report the values obtained and the method used to determine vapor pressure of sea water for different concentrations for this temperature range.

II. APPARATUS

1. General Description.

The determination of vapor pressure was carried out with static type

vapor pressure apparatus of essentially the type used by Gibson and Adams, 1933. Slight modifications of the Gibson and Adams technique included the use of a somewhat different solution container and a manometric oil of lower density. Dissolved gases were removed from the sample by the method suggested by Hibben, 1929. This consisted of a vacuum sublimation of the solution. A new type of solution cell was designed in order to carry out both the degassing and vapor pressure measurement in the same container.

A schematic diagram of the apparatus is shown in Figure 1 and two photographs of the apparatus (Figures 2 and 3) show the actual arrangement of the various components. The apparatus consisted of a thermostated bath which maintained thermal equilibrium between pure water sample and sea water at any desired temperature. The test solutions remained in the solution cells during both the operations of degassing and vapor pressure measurement.

The manometer measured the pressure differential between a solution and the vacuum. Two flasks containing water were used as auxiliary sources of water vapor to assist in obtaining rapid equilibrium in the system. A cathetometer was used to determine the difference in height of the two oil levels in the manometer.

2. Details of Construction.

In order to obtain relatively good pumping speeds when evacuating the system, 10 millimeter glass tubing and stopcocks of 4 millimeter bore were used.

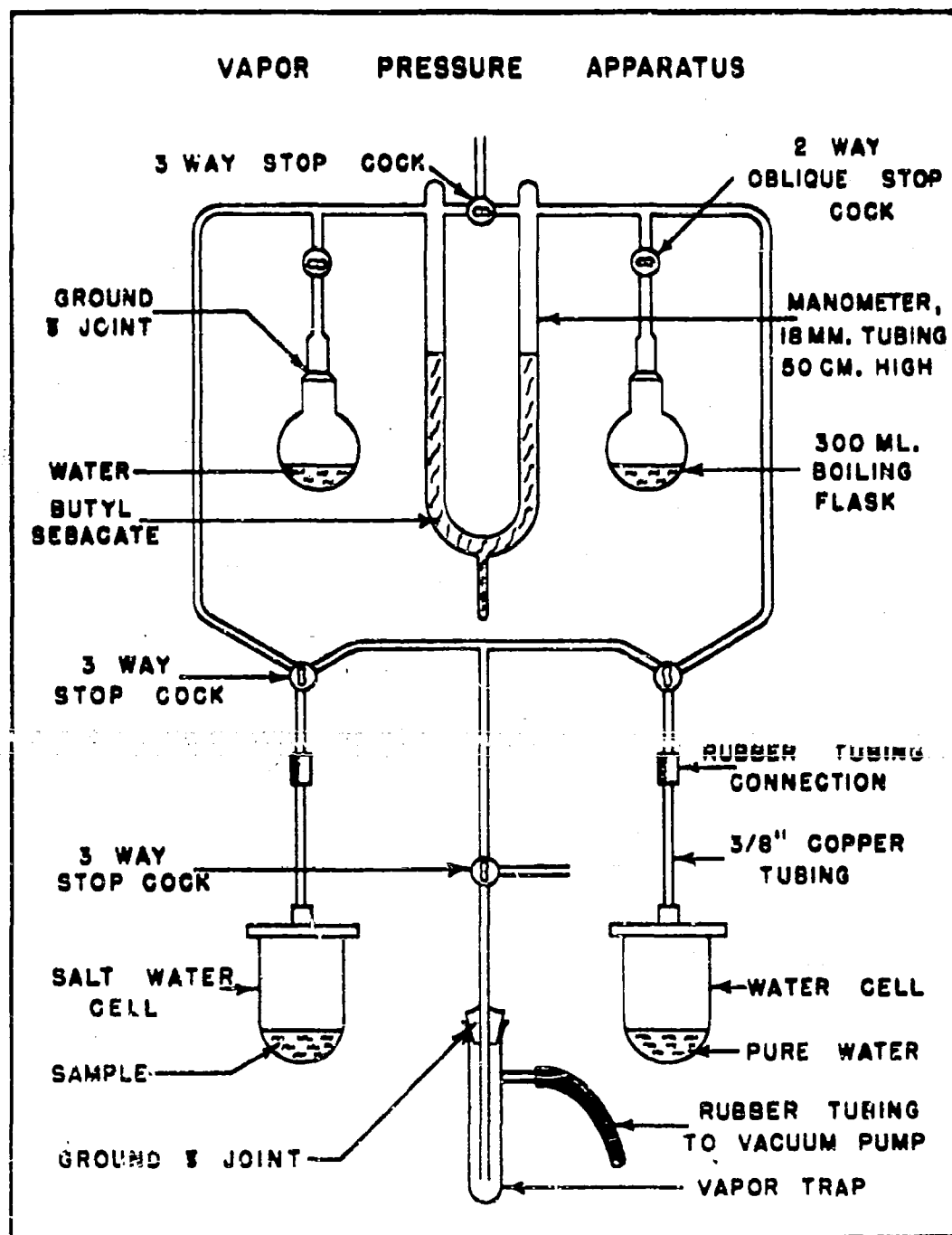


FIG. 1

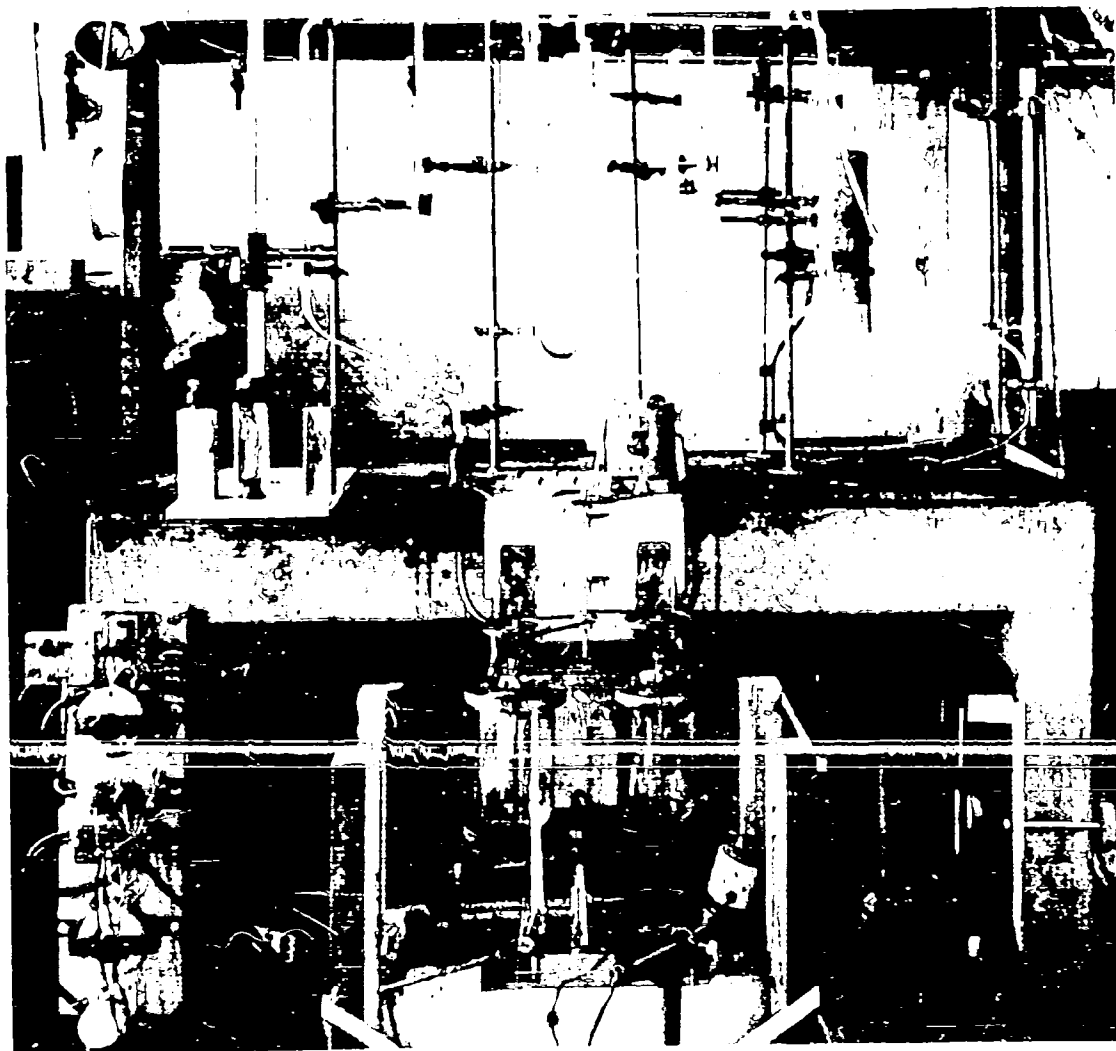


FIG.2

Vapor pressure apparatus, showing vacuum system, solution cells, control panel, and constant temperature bath.

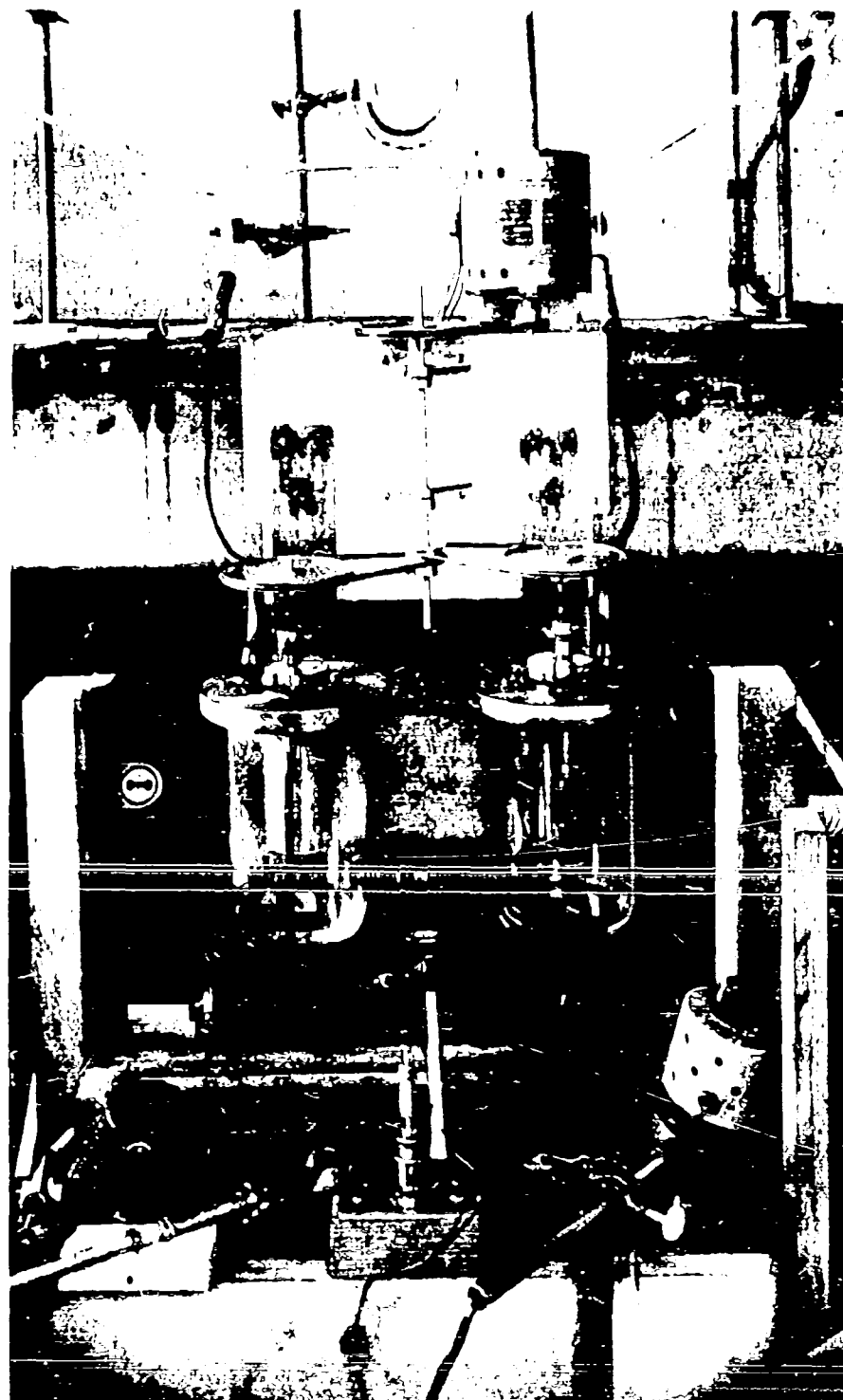


FIG.3

Close-up of solution cells.

The two primary requirements for a suitable manometer oil are: (a) extremely low vapor pressure, (b) lowest possible density. Butyl sebacate, which has a density of .933 at 25°C, was selected. The manometer was constructed of 18 millimeter OD tubing to minimize capillary rise. This size was recommended by Gibson and Adams (1933).

The oil drain at the bottom of the manometer consisted of glass tubing, sealed at the end. It was originally intended to use a stopcock at this point but it was found that the butyl sebacate manometric fluid dissolved the stopcock lubricant and caused leakage of air into the system.

The 300 millimeter auxiliary water flasks were attached to the system through a ground glass joint. This enabled the water to be introduced into these flasks easily.

The vapor trap was cooled with dry ice and alcohol mixture to produce a temperature of about -72°C, sufficiently low to prevent any moisture from reaching the vacuum pump. A vacuum gauge tube, thermocouple type (RCA-1946), located on the pump side of the vapor trap, measured the residual gas pressure. Pumping was done by means of a Cenco Hyvac.

The solution cells, a diagram of which is shown in Figure 4, were of the authors' design. The glass containers consisted of 100 millimeter pyrex tubing, one end closed off with a test tube seal. Tubing was used instead of a more readily available bell jar because the thinner walls allow more rapid attainment of thermal equilibrium between the test solution and the thermostated bath.

The brass cell cover contained the fittings for the vacuum line, rotary vacuum seal, and the plug. A cylindrical brass reservoir, projecting

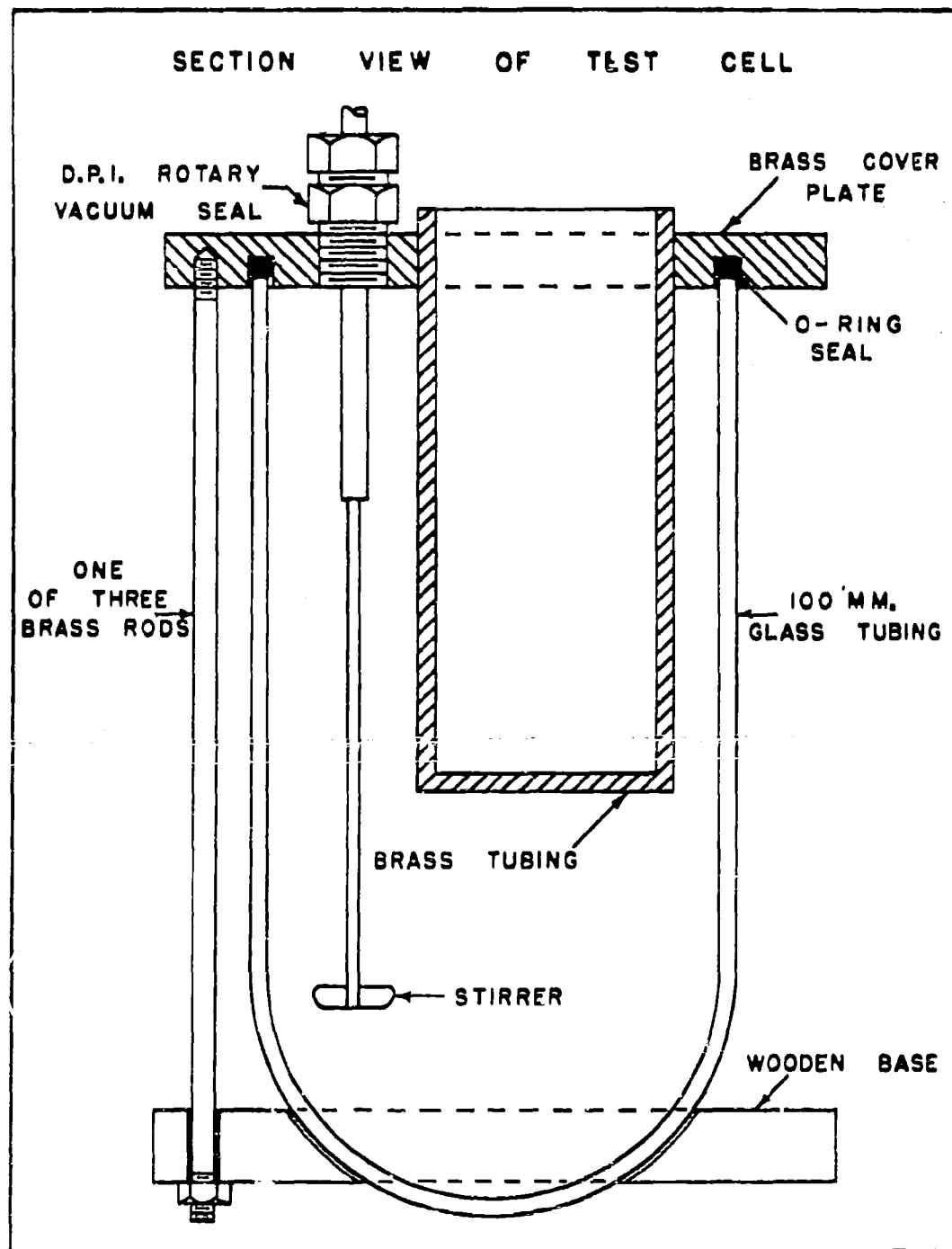


FIG. 4

downward into the cell provided the surface for the vacuum sublimation. The seal between the glass tubing and the brass cover consisted of an O-ring recessed in a groove well packed with vacuum grease.

Stirring the solution in the cells was accomplished by means of the motor and pulley arrangement shown in Figure 2. The cells were connected to the vacuum system with copper tubing which was in turn coupled to the glass tubing with vacuum rubber hose.

The cathetometer was a commercial model with a range of 40 centimeters and an accuracy of ± 0.1 millimeters. The instrument was mounted adjacent to the manometer. The difference in the height of the two columns was obtained by first ascertaining the height of one column, revolving the telescope through a small horizontal angle, and then determining the height of the other column. The leveling of the instrument was checked periodically by equalizing the pressure on both sides of the manometer and noting if the reading of the height of each column coincided on the cathetometer.

The constant temperature bath, the top of which is visible in the lower part of Figure 3, contained 10 gallons of ethylene glycol-water solution. The tank was surrounded by 1/2 inch of insulation and a wooden box. The heating element was a 250 watt knife heater. Two stirring motors were used to keep the solution well agitated. Temperature regulation was obtained with a mercury thermo-regulator, which activated a relay, and which in turn controlled the current to the knife heater. The entire bath was set in vertical guides so that it could be raised to immerse the cells completely.

The refrigerator was a 1/4 horsepower freon unit, with sufficient capacity to handle the entire range of temperatures used in this work. An adjustable expansion valve and gauge were mounted on the side of the tank and six turns of copper tubing in the tank served as the cooling coils.

The temperature in the tank was readily controlled to $\pm 0.007^{\circ}\text{C}$. The maximum variation of the tank temperature was determined by a recording potentiometer and a thermocouple. The two thermometers used to determine the tank temperature were supplied with Bureau of Standards tabular corrections. The 0 - 50°C thermometer was read to 0.01°C , while the -30° to 50°C thermometer was read to 0.02°C . A stem correction, of the order of several hundredths of a degree, was made on each observation.

III. CALIBRATION OF THE MANOMETER

Determination of the density of the manometric fluid was made by the pycnometer flask method. The volume of a pyrex flask was determined by filling it with distilled water, immersing it in the constant temperature bath, weighing it to obtain the gross weight, and from this obtaining the net weight of the water. From the known density at this temperature, the volume was determined. This procedure was repeated for the butyl sebacate at different temperatures and the density at each temperature was calculated. The correction for change in volume of the flask was negligible. The curve of density versus temperature is given in Figure 5.

The manometer was prepared for measurement by introducing the oil through the stopcock above the manometer. In order to expel the dissolved

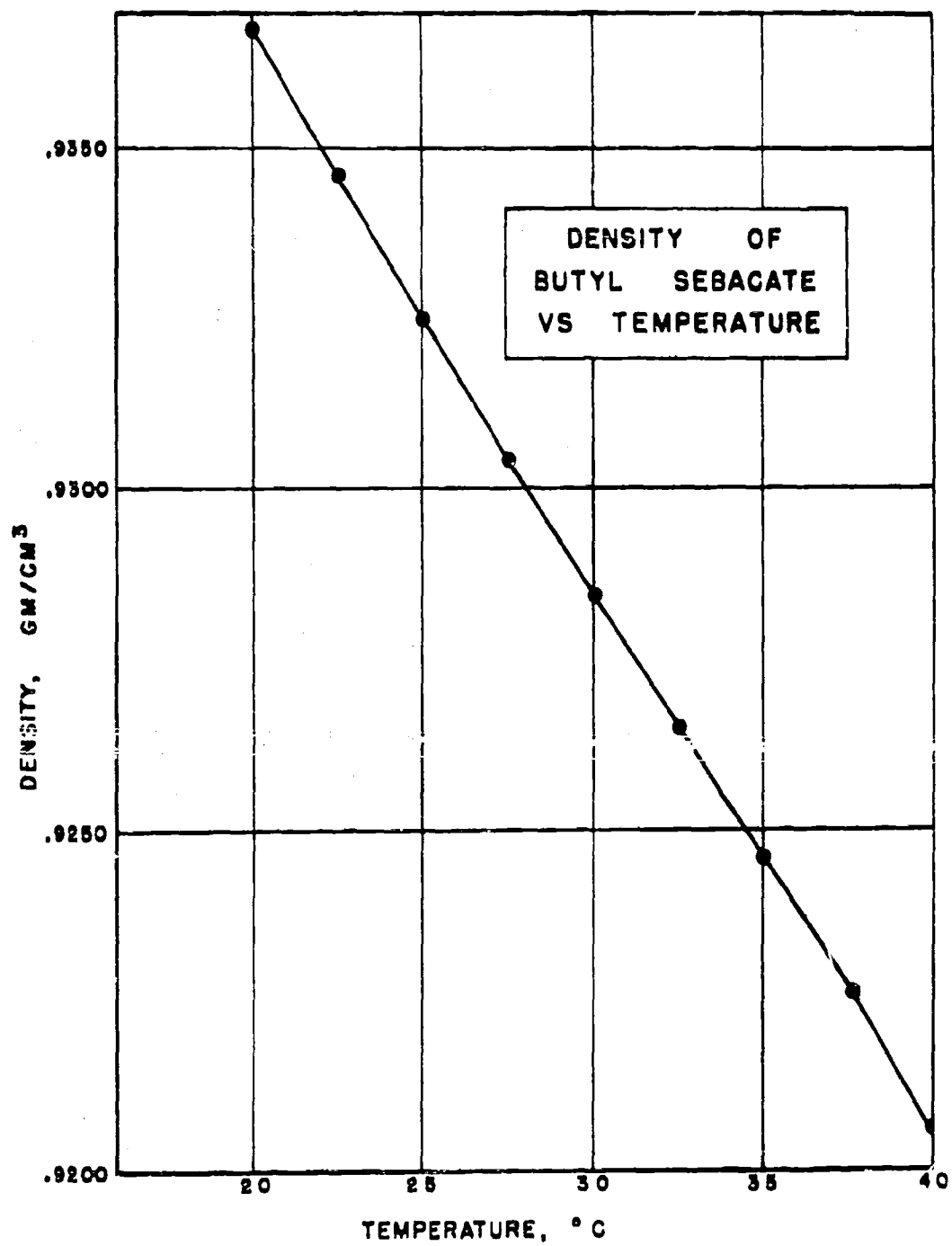


FIG. 5

gases in the oil, the system was evacuated; the manometer oil was warmed for a short period of time, and a high vacuum was maintained by continued pumping for a period of one day. Care was taken never to expose the system to atmospheric pressure once the manometer oil had been degassed.

IV. EXPERIMENTAL PROCEDURE

1. Preparation and Titration of Samples

The preparation of samples consisted of obtaining sea water varying in concentration from sea water itself to a saturated solution. Attempts were made to use a formula for artificial sea water (Lyman and Fleming, 1940) to obtain the concentrated solutions, but large amounts of precipitate were observed in the concentrated solutions, and the use of artificial sea water was abandoned.

The samples were prepared from natural sea water obtained at Woods Hole, Massachusetts. The concentration of the first six samples of sea water (which had been previously filtered to remove the organic matter) was carried out in 2000 milliliter Erlenmeyer flasks heated over a low flame. The other five samples were concentrated in boiling flasks by passing air through the solution and maintaining a temperature of 80°C . It was found that the saturation point was at about 10 times the normal concentration, or at a chlorinity of about 155 ‰. For concentrations of 40 ‰ or greater some precipitate appeared. Thompson (1932) states that CaCO_3 is first deposited, followed by $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ at a concentration of about 70 ‰.

The concentrated solutions and their precipitates were stored in 500 milliliter flasks. The samples for vapor pressure measurements were

decanted at room temperature and did not contain any precipitates which might have interfered in the titration of samples.

Concentration of the samples was determined by titration with silver nitrate solution. The silver nitrate was standardized against secondary standard sea water. The density of the concentrated solutions was obtained from Higashi, et al (1931).

The accuracy of the sea water titrations was determined to be about 0.05% by comparing results with those obtained by the Woods Hole Oceanographic Institution's salinity determination laboratory.

2. Degassing of Samples and Auxiliary Flasks

Degassing of the samples was carried out in the following manner: the samples were introduced by pipette through the hole in the solution cell covers, and the system was then sealed. A small pail containing a mixture of water and dry ice was suspended around the solution cell. After the sample was at the freezing point for a period of time, the three-way stopcock was opened momentarily to produce a partial vacuum in the solution cell. This liberated a fairly large quantity of gas from the solution.

At this point, a mixture of dry ice and alcohol was introduced into the brass tubing reservoir which projects down into the cell. This produced immediate condensation and freezing of water vapor on the brass tubing. The vacuum of the system was then applied to the cell. Rapid evaporation from the surface of the solution caused the solution to freeze in a matter of seconds. At this point, the vapor pressure of the ice, which was forming on the wall of the reservoir, was a fraction of a

millimeter. It was now necessary to heat the water on the outside of the solution cell in order to speed up the sublimation process. The sublimation process was continued until the last of the ice crystals disappeared from the bottom of the glass cell. The solution cell was then shut off from the vacuum system and warm water and dry ice-alcohol mixture were removed, thus allowing the ice that had frozen on the cold wall to melt and return to the bottom of the cell.

For the pure water sample, this process required about 12 hours, while for the sea water solution it required about 4 or 5 hours, depending upon the concentration of the solution.

Degassing of the salt solutions produced deposits of salt along the walls of the glass above the solution level. These deposits were washed back into the solution by shaking the cell slightly. Also, cooling the upper portion of the wall caused moisture to condense and run down the wall, assisting in washing the salt back into the solution.

Degassing the water in the auxiliary flasks was carried out in the manner suggested by Gibson and Adams, that is, freezing under vacuum. The following procedure was used to degass these flasks: pure water was placed in the flask; a vacuum was applied to the solution liberating a fair quantity of gas. A mixture of dry ice and alcohol was placed around the flask causing the water to freeze. The flasks were sealed, dry ice mixture removed, and water allowed to melt. This process was repeated 3 or 4 times.

3. Determination of Vapor Pressure.

The determination of vapor pressure for each sample was made at 5°

intervals from a temperature of 30°C , to the freezing point of the solution.

The constant temperature bath was raised until the level of the bath was up to the top of the cell covers. The temperature of the bath was set at some specific value, and the stirring motors were started. Thermal equilibrium was reached in about $\frac{1}{2}$ hour and the three-way stopcock of the salt solution cell was then turned so that it was connected to one leg of the manometer. The other leg of the manometer was on the high vacuum side.

A short blast of water vapor from the auxiliary flask helped the system to reach pressure equilibrium rapidly, and when equilibrium was reached, cathetometer readings were made of the manometer levels. The manometer oil temperature was read with a small thermometer securely fastened to the manometer itself. The bath temperature and the ambient temperature above the surface of the liquid were also observed. This procedure was then repeated for the pure water sample.

The differential pressure measurement was obtained with the pure water sample connected to one leg of the manometer and the sea water sample connected to the other. As a check on those measurements, the observed pressure of pure water was checked with the values for vapor pressure of water given in "Handbook of Chemistry and Physics". The difference between observed sea water vapor pressure and pure water vapor pressure was the vapor pressure lowering, and this value was checked with the value obtained from the differential method directly.

For temperatures below 0°C , the bath was brought to several degrees below freezing and held there several hours, thus allowing the pure water

sample to freeze. The readings were taken in the manner previously described. The pressure difference was no longer vapor pressure lowering but the difference between vapor pressure of the solution and vapor pressure of ice. In order to obtain vapor pressure lowering, relative to pure water, the difference between the vapor pressure of ice and water was added to the observed pressure differential. The vapor pressure of ice was also checked with the published values and excellent agreement was observed.

It was found that the samples of high concentration required less time to achieve equilibrium than those of low concentration. The time was of the order of 1 hour for the former and about 24 hours for the latter.

To check the reproducibility of the results, measurements were made at the same temperature on the same sample several days apart. In most cases the values checked within $\pm 2\%$.

A check was made on the completeness of the degassing of a sample after a series of measurements had been made. It was found that a second and even third degassing produced no significant effect on the observed vapor pressure. The degassing of the pure water sample was assumed complete since its observed vapor pressure consistently checked with published values.

The concentration of the sample was determined both before it was placed in the solution cell and also after the completion of the vapor pressure measurements. The fact that the concentration did not change significantly showed that this method of degassing results in a negligible loss of solvent.

V. EXPERIMENTAL RESULTS

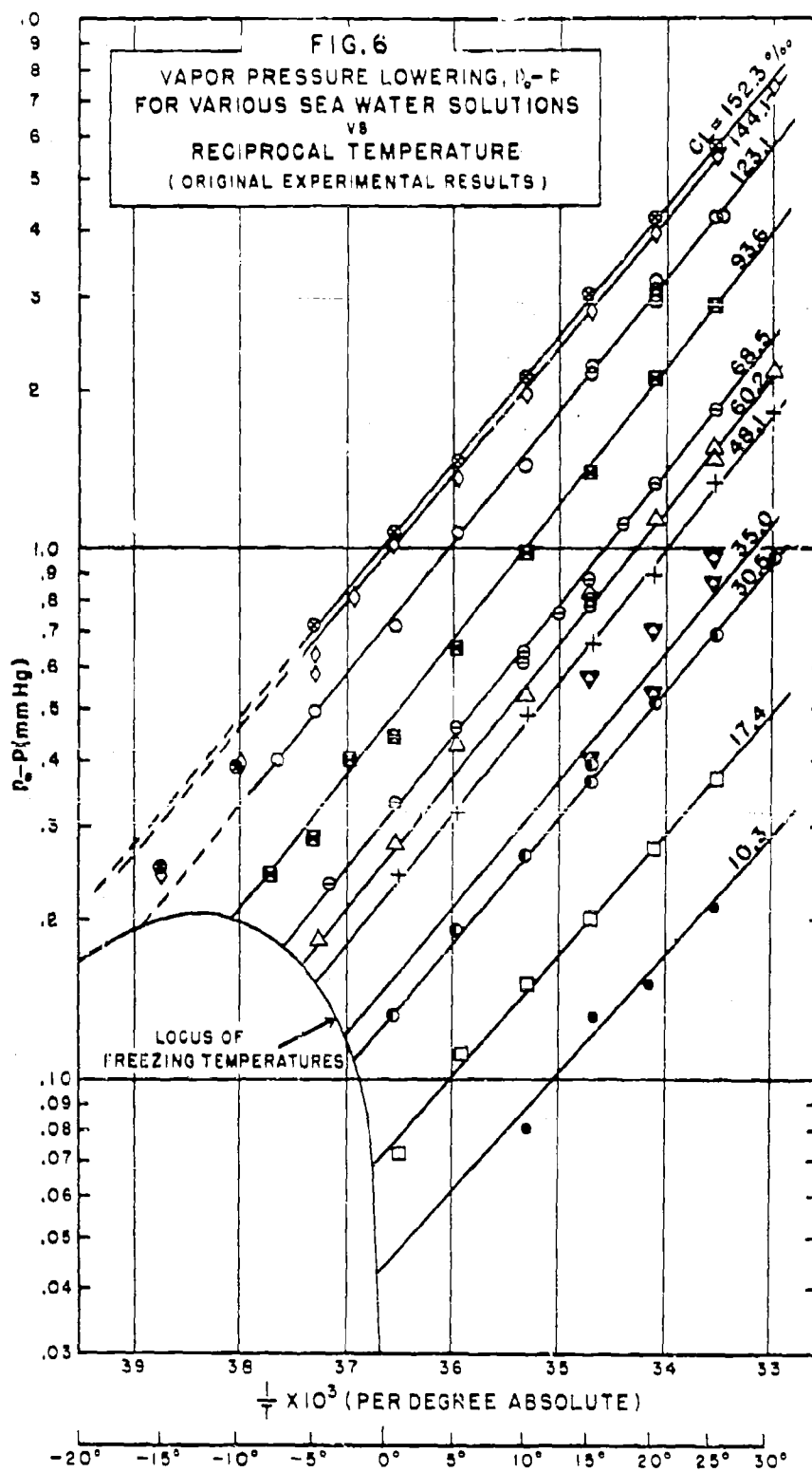
Integration of the Clausius-Clapeyron equation yields the relation:

$$\ln p = \frac{-L}{RT} + C \quad (1)$$

where p is pressure, T is temperature, R is the gas constant, L is the latent heat of evaporation, and C a constant of integration. It is evident from equation (1) that if vapor pressure is plotted against reciprocal of absolute temperature on semilogarithmic paper, the result will be a straight line to a first order approximation, since the latent heat does not vary greatly in the temperature interval under consideration. Therefore the vapor pressure of solutions of different concentrations, if plotted on semilogarithmic paper, will form a family of lines each displaced from the vapor pressure of pure water. A plot of vapor pressure lowering versus $1/T$ will also be very nearly a straight line.

At the freezing point of a solution the vapor pressures of the solution and of pure ice are the same. From published freezing point equations (Thompson, 1932; Hansen, 1904), the vapor pressure lowering may be determined. For chlorinities of 35 ‰ and less, where these equations are valid, the computed values agreed well with our experimental results.

The original experimental points are given in Appendix 2 and are shown plotted on semilogarithmic coordinates in Figure 6. In order to obtain the values of vapor pressure lowering for solutions of various other concentrations, it was necessary to interpolate between the original curves of Figure 6. A cross plot of vapor pressure lowering versus the

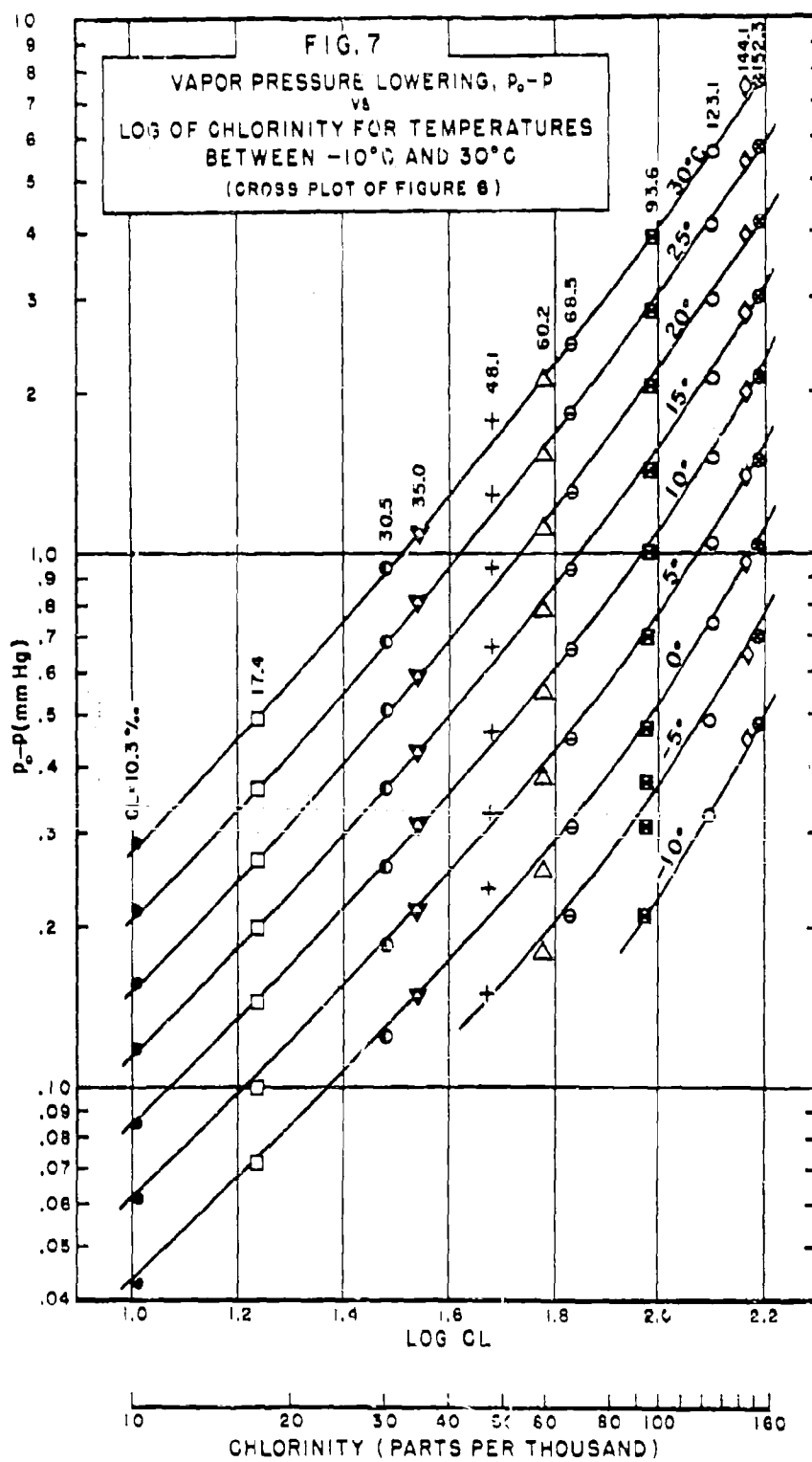


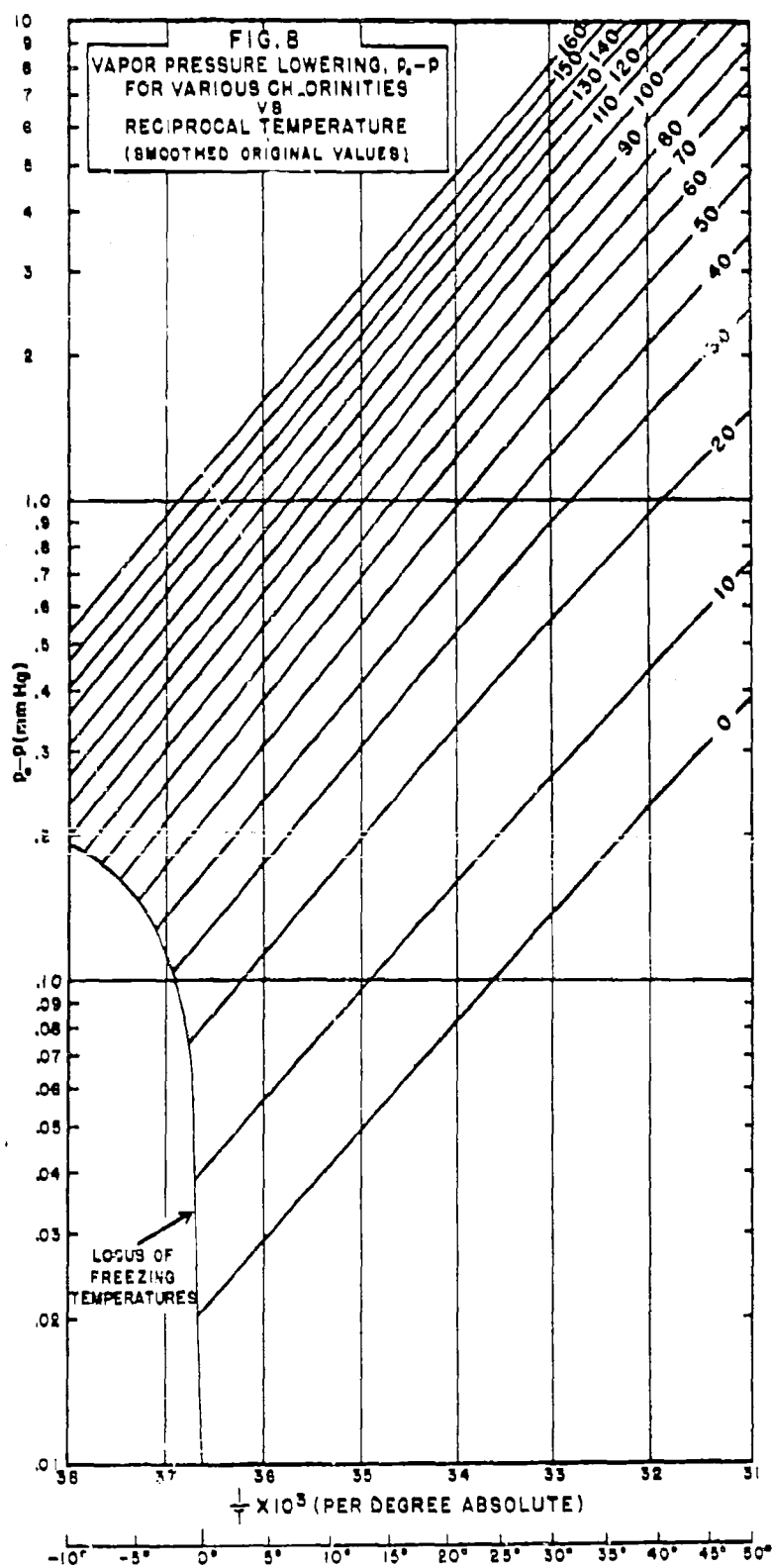
logarithm of chlorinity (Figure 7) was obtained from Figure 6. Vapor pressure lowering for various integral values of chlorinity was then obtained from the smoothed curves of Figure 7. The latter values are plotted and smoothed on semilogarithmic coordinates in Figure 8. A table of values on which Figure 8 is based is given in Table 1 of Appendix 1.

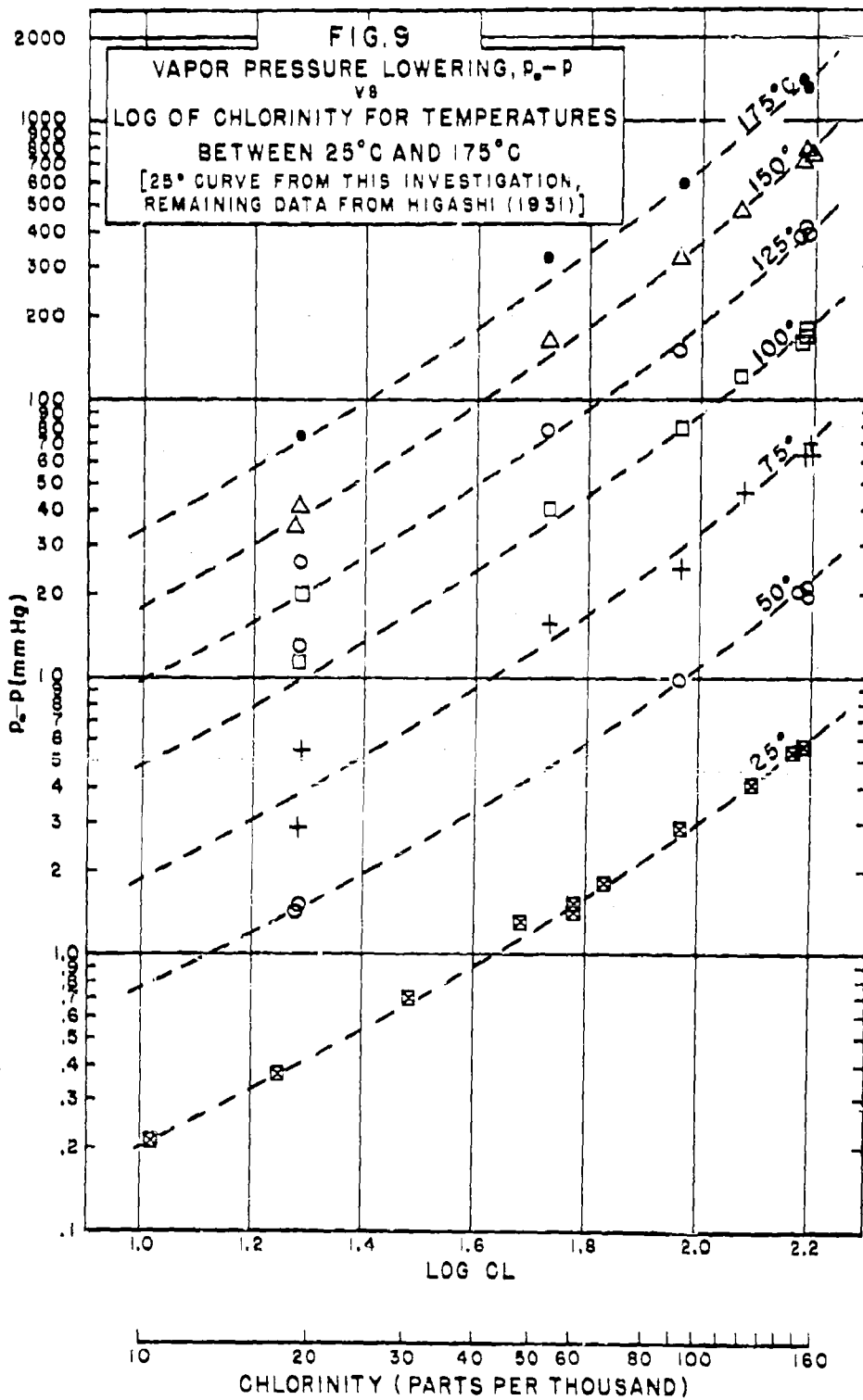
Before the techniques of degassing and insuring pressure equilibrium in the system were perfected, runs on some of the early samples showed a very large scatter (as, for example, the $Cl = 35$ ‰ points in Figure 6). All experimental results have been included in Figure 6 for completeness, but principal weight in smoothing and in determining the slopes of the curves has been given to the later, more reproducible measurements.

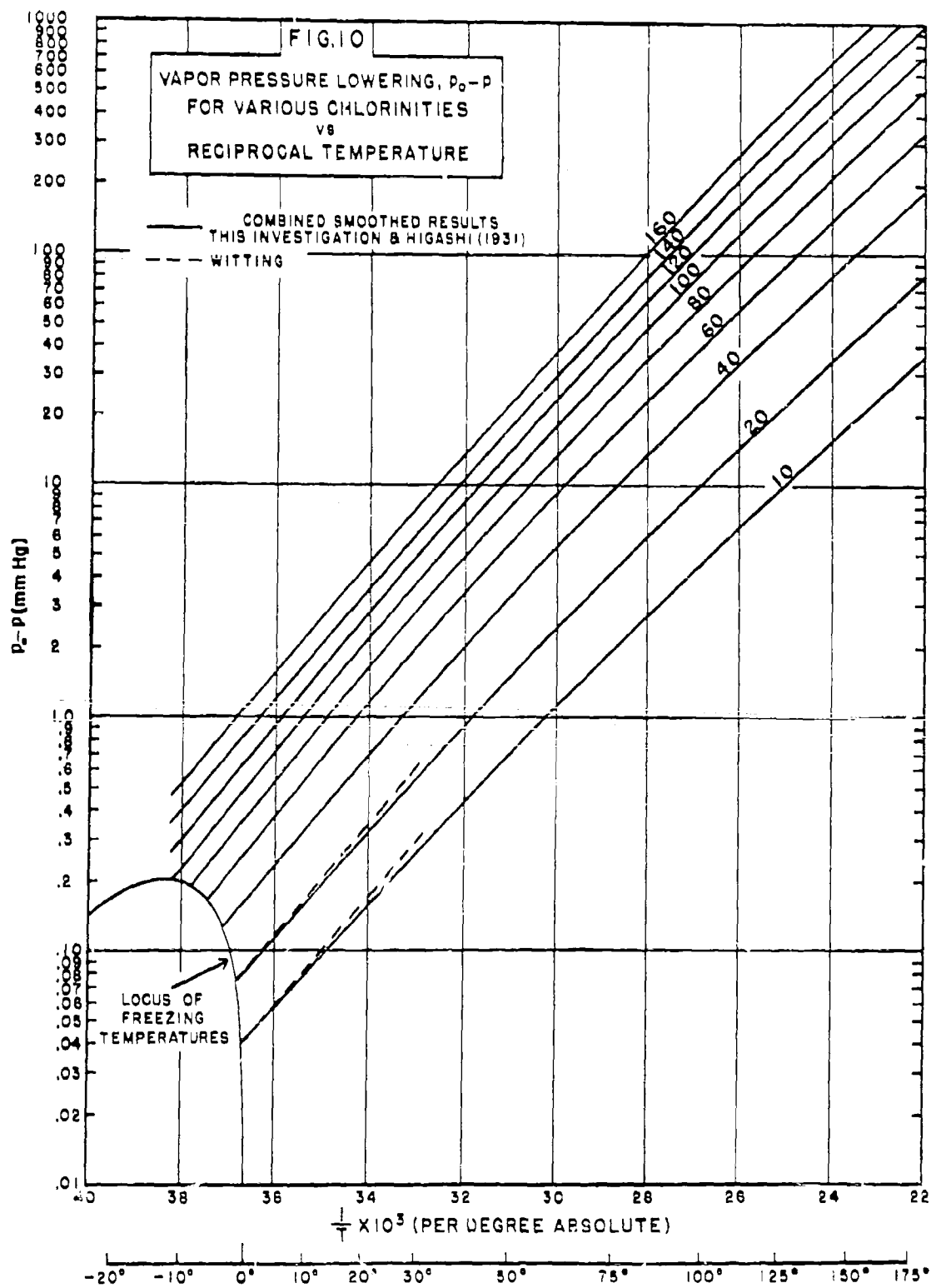
Because of the inaccessibility of Higashi's data (1931) in the original publication, it was deemed desirable to rework his data and tie them in with the results of this investigation, thus supplying values of vapor pressure lowering in the temperature range between $30^{\circ}C$ and $175^{\circ}C$ as well as between freezing and $30^{\circ}C$.

In re-examining Higashi's smoothed values and original experimental results, various large discrepancies were noted, and his $25^{\circ}C$ measurements were found to show exceedingly large scatter. It was therefore decided to re-smooth Higashi's data, substituting our $25^{\circ}C$ results for his. The resulting plot of vapor pressure lowering versus log of chlorinity is shown in Figure 9. The results of Figure 9 were further smoothed by cross plotting, and the final smoothed curves, combining both our data and Higashi's for temperatures from freezing to $175^{\circ}C$ are shown in Figure 10. The table of values on which Figure 10 is based is given in Table 2 of Appendix 1. Higashi's original results are reproduced in Appendix 3.









R. Witting (1908) obtained a relationship between concentration and vapor pressure lowering by utilizing the pertinent thermodynamic equations (Ostwald, 1899) and an experimental relationship between chlorinity and freezing point lowering (Hansen, 1904). Witting's relationship is given in Appendix 4 and is also plotted in Figure 10. It was found that for dilute solutions (chlorinity of 20 or less) there was quite good agreement between the Witting equation and our results in the temperature range between 0°C and 30°C.

In view of the smoothing processes used in obtaining the final values of vapor pressure lowering, it is difficult to make an objective estimate of the accuracy of the results, but the authors feel this to be of the order of 2%.

VI. ACKNOWLEDGMENT

The authors wish to thank Messrs. Charles Keith and Alfred Woodcock for their helpful advice regarding experimental problems and their general interest in the investigation.

Appendix 1

Tabulated Values Used in Plotting Figures 8 and 10

Table 1

Values of vapor pressure lowering used in Figure 8
(Results of this investigation)

Chlorinity ‰	Pressure in mm. of Hg.									
	Temperature °C									
-	35°	30°	25°	20°	15°	10°	5°	0°	-5°	-10°
5	0.18	0.13	0.10	0.08	0.06	0.04	0.03	0.02	-	-
10	0.35	0.27	0.20	0.15	0.11	0.08	0.06	0.04	-	-
20	0.74	0.56	0.43	0.32	0.23	0.16	0.12	0.08	-	-
30	1.20	0.90	0.68	0.49	0.36	0.26	0.18	0.12	-	-
40	1.67	1.25	0.92	0.67	0.49	0.35	0.24	0.17	-	-
50	2.24	1.67	1.24	0.90	0.65	0.45	0.31	0.22	0.15	-
60	2.87	2.14	1.58	1.14	0.81	0.57	0.39	0.27	0.18	-
70	3.45	2.57	1.88	1.36	0.96	0.68	0.47	0.32	0.22	-
80	4.08	3.04	2.25	1.62	1.16	0.81	0.56	0.38	0.26	-
90	4.87	3.65	2.67	1.92	1.37	0.95	0.66	0.44	0.30	0.20
100	5.64	4.17	3.07	2.20	1.57	1.10	0.76	0.52	0.35	0.23
110	6.50	4.81	3.52	2.55	1.82	1.27	0.87	0.59	0.40	0.27
120	7.29	5.44	4.03	2.91	2.07	1.44	1.00	0.68	0.46	0.31
130	8.17	6.09	4.50	3.28	2.36	1.67	1.16	0.79	0.54	0.36
140	8.89	6.71	4.99	3.63	2.62	1.85	1.28	0.88	0.60	0.41
150	9.93	7.42	5.52	4.01	2.93	2.08	1.47	1.02	0.69	0.46
160	10.73	8.20	6.14	4.49	3.27	2.33	1.65	1.14	0.79	0.53

Appendix 1 (cont.)

Table 2

Values of vapor pressure lowering used in Figure 10
(Re-smoothed results of Higashi)

Chlorinity ‰	Pressure in mm. of Hg.							
	Temperature °C							
-	175°	150°	125°	100°	75°	50°	25°	0°
10	33.0	18.5	9.7	4.75	1.99	0.74	0.20	0.04
20	72.6	41.0	21.1	10.2	4.40	1.54	0.43	0.08
30	118	65.8	34.0	16.4	7.08	2.50	0.68	0.12
40	168	94.5	49.3	23.9	9.99	3.58	0.92	0.17
50	227	128	66.5	32.1	13.2	4.75	1.24	0.22
60	298	168	86.2	41.0	16.6	5.96	1.58	0.27
70	374	213	108	52.0	21.1	7.41	1.88	0.32
80	457	257	132	62.2	25.1	8.85	2.25	0.38
90	551	308	157	74.7	30.1	10.3	2.67	0.44
100	640	363	184	87.4	34.8	11.7	3.07	0.52
110	749	425	217	103	41.1	13.6	3.52	0.59
120	868	486	248	117	46.3	15.2	4.03	0.68
130	1000	568	287	135	53.7	17.2	4.50	0.79
140	1115	630	317	151	58.4	18.8	4.99	0.88
150	1260	722	365	170	65.4	20.9	5.52	1.02
160	1440	822	408	188	72.8	22.8	6.14	1.14

Appendix 2

Original Vapor Pressure Data Obtained
in this Investigation

Pressure in mm. of Hg.
Chlorinity in parts/thousand

Corrected Temperature °C	Observed Water - *Ice V.P. p'_0	Observed Sample V.P. p	Observed Differential $p'_0 - p$	Average Corrected $p_0 - p$
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Sample #2 Cl. = 35.0

20.00	17.57	17.05	0.49	0.50
14.98	12.79	12.41	0.40	0.39
19.99	17.57	16.79	0.83	0.80
19.99	17.55	16.83	0.70	0.71
20.00	17.56	17.06	0.51	0.50
24.99	23.78	22.89	0.86	0.88
20.01	17.57	17.02	0.53	0.54
24.99	23.79	22.80	0.95	0.97
15.00	12.81	12.46	0.36	0.36
10.01	9.23	8.98	0.25	0.25
4.98	6.53	6.39	0.14	0.14
0.49	4.75	4.66	0.09	0.09
15.01	12.83	12.21	0.57	0.60
9.96	9.20	8.98	0.25	0.24

Sample #6 Cl. = 93.6

20.01	17.59	15.44	2.08	2.12
15.02	12.80	11.41	1.39	1.39
9.99	9.19	8.24	0.97	0.96
4.97	6.53	5.88	0.64	0.64
0.47	4.75	4.30	0.44	0.44
-8.02	* 2.32	2.26	0.05	0.24
-5.04	* 3.01	2.79	0.20	0.36
-2.50	* 3.73	3.41	0.31	0.40
-5.01	* 3.01	2.89	0.13	0.28
25.00	23.78	20.93	2.86	2.86

Sample #4 Cl. = 68.5

20.00	17.54	16.43	1.10	1.10
14.99	12.79	12.02	0.77	0.77
9.99	9.20	8.54	0.63	0.64
14.98	12.78	11.99	0.79	0.79
9.98	9.20	8.60	0.60	0.60

Appendix 2 (cont.)

Corrected Temperature °C	Observed Water - *Ice V.P. p'_o	Observed Sample V.P. p	Observed Differential $p'_o - p$	Average Corrected $P_o - p$
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Sample #4 Cl. = 68.5 (cont.)

4.99	6.54	6.08	0.45	0.46
0.48	4.76	4.42	0.33	0.34
-3.99	* 3.29	3.17	0.10	0.24
19.98	17.51	16.18	1.32	1.32
25.02	23.82	22.02	1.82	1.81
15.01	12.82	12.01	0.86	0.84
15.00	12.81	12.01	0.81	0.80
19.99	17.54	16.21	1.31	1.32
14.99	12.79	12.00	0.83	0.81
12.51	10.91	10.15	0.75	0.76
17.49	15.00	13.94	1.11	1.08

Sample #8 Cl. = 123.1

20.01	17.56	14.63	2.92	2.92
15.00	12.81	10.67	2.13	2.14
10.01	9.22	7.79	1.43	1.43
4.98	6.55	5.48	1.06	1.06
0.47	4.77	4.05	0.71	0.72
-9.99	* 1.97	1.96	0.00	0.20
-7.49	* 2.44	2.21	0.22	0.40
-4.97	* 3.03	2.67	0.34	0.50
20.00	17.56	14.35	3.18	3.20
24.99	23.73	19.51	4.19	4.20
20.01	17.56	14.56	2.97	2.98
20.00	17.56	14.53	3.04	3.04
15.00	12.79	10.59	2.20	2.20

Sample #10 Cl. = 152.3

24.98	23.75	18.09	5.64	5.65
19.99	17.52	13.39	4.17	4.15
14.99	12.79	9.81	2.99	2.98
10.00	9.22	7.12	2.11	2.11
4.98	6.54	5.07	1.47	1.47
0.49	4.76	3.68	1.08	1.08
-5.00	* 3.03	2.46	0.58	0.72
-9.99	* 1.95	1.69	0.26	0.46
-15.02	* 1.25	1.19	0.05	0.25

Appendix 2 (cont.)

Corrected Temperature °C	Observed Water - *Ice V.P. P'_0	Observed Sample V.P. P	Observed Differential $P'_0 - P$	Average Corrected $P_0 - P$
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Sample #1 $Cl. = 17.4$

20.00	17.54	17.28	0.27	0.26
20.01	17.55	17.28	0.27	0.27
14.98	12.78	12.58	0.20	0.20
0.48	4.76	4.69	0.07	0.07
4.98	6.55	6.44	0.11	0.11
9.97	9.19	9.03	0.15	0.16
25.00	23.75	23.38	0.37	0.37

Sample #10-A $Cl. = 14.1$

20.00	17.56	13.67	3.87	3.88
15.02	12.87	10.02	2.82	2.84
15.02	12.80	10.02	2.82	2.80
12.22	17.52	13.66	3.86	3.92
10.01	9.24	7.32	1.94	1.96
-14.98	* 1.27	1.22	0.03	2.24
-10.07	* 1.96	1.76	0.18	0.39
-5.01	* 3.00	2.57	0.42	0.58
0.48	4.76	3.72	1.05	1.04
4.98	6.53	5.17	1.38	1.37
-4.97	-	2.55	-	0.62
25.00	23.79	18.30	5.50	5.50
30.00	-	-	7.40	7.40
-2.49	-	3.01	-	0.81

Sample #2-A $Cl. = 30.5$

20.01	17.57	17.07	0.48	0.49
24.99	23.76	23.05	0.68	0.70
29.99	-	-	0.95	0.95
14.94	12.74	12.39	0.36	0.36
10.03	9.22	8.96	0.26	0.26
4.99	6.54	6.34	0.18	0.19
0.53	4.76	4.63	0.13	0.13
15.00	12.80	12.40	0.38	0.39
20.02	17.56	17.05	0.51	0.51

Appendix 2 (cont.)

Corrected Temperature °C	Observed Water - *Ice V.P. P'_0	Observed Sample V.P. P	Observed Differential $P'_0 - P$	Average Corrected $P_0 - P$
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Sample #4-A Cl. = 60.2

24.99	23.77	22.31	1.44	1.45
20.03	17.57	16.42	1.12	1.14
15.01	12.79	11.95	0.81	0.82
10.04	9.25	8.73	0.53	0.52
5.05	6.55	6.12	0.42	0.42
-4.96	* 3.06	3.03	0.03	0.18
0.45	4.75	4.48	0.28	0.28
30.00	-	-	2.15	2.15
24.98	23.76	22.23	1.51	1.52

Sample #3 Cl. = 48.1

19.98	17.49	16.59	0.88	0.89
14.90	12.77	12.10	0.65	0.66
10.03	9.33	8.84	0.47	0.48
5.10	6.57	6.24	0.32	0.32
0.59	4.74	4.50	0.24	0.24
24.98	23.69	22.34	1.31	1.33
29.96	-	-	1.79	1.79

Sample #1 Cl. = 10.3

24.97	23.73	23.55	0.23	0.21
19.79	17.29	17.15	0.15	0.15
15.28	12.98	12.86	0.14	0.13
9.98	9.17	9.09	0.08	0.08

Appendix 3

Higashi's Original Vapor Pressure Data

Chlorinity parts/thousand	Temperature °C	Vapor pressure lowering mm. of Hg.
19.40	24.97	0.6
"	49.86	1.4
"	75.65	2.8
"	99.19	11.2
"	126.14	12.9
"	150.26	34.6
19.87	24.17	0.7
"	50.18	1.5
"	75.03	5.4
"	99.33	14.7
"	125.09	25.8
"	150.34	40.3
"	175.22	72.0
53.04	24.85	1.4
"	74.09	15.5
"	100.02	40.0
"	124.16	76.3
"	149.24	162.8
"	176.41	315
104.24	24.24	2.1
"	50.15	9.9
"	75.23	35.1
"	124.67	206
"	150.30	407
119.16	75.00	46.1
"	100.16	122.4
"	149.06	474
151.82	25.66	5.2
"	50.00	21.3
"	74.94	62.6
"	99.70	160.7
"	125.99	386
"	148.27	699
"	176.09	1360
154.32	24.94	3.9
"	49.67	20.8
"	74.80	62.4
"	100.05	169.1
"	125.97	396
"	148.36	739
"	172.45	1295
155.69	25.14	5.1
"	49.72	21.7
"	75.64	69.6
"	99.95	175.9
"	126.22	412
"	147.50	753

Appendix 4

Relationship between Vapor Pressure and
Concentration for Sea Water

R. Witting (1908)

$$p = p_0 (1 - 0.000537 S)$$

S is salinity in parts/thousand

$$p = p_0 (1 - 0.000969 Cl.)$$

Cl. is chlorinity in parts/thousand

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